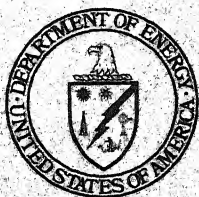


Trapped Particle Instabilities Workshop

February 12 and 13, 1979
Germantown, Maryland

Publish, May 1979



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U.S. Department of Energy
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TRAPPED PARTICLE INSTABILITIES WORKSHOP

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Walter L. Sadowski

Introduction

A workshop was held in Germantown on February 12 and 13, 1979, to review past history, present status and future directions of the field of trapped particle instabilities.

Trapped particle instabilities are one member of a group of low-frequency microinstabilities that may contribute to anomalous transport. Although the emphasis was on trapped particle instabilities, the discussion included the relative contribution to anomalous transport by other low-frequency microinstabilities. On the second day of the meeting, the workshop addressed 12 specific questions dealing with the relevance of trapped particle instability theories to present and future devices. A question-by-question summary is included in the appendix. The appendix provides the basis on which the summary was written.

Usually in a scientific program advances are based on an interplay between theory and experiment. Theoretical predictions concerning isolated phenomena are checked by experiment and experimental data reflecting the interplay of many phenomena are in turn interpreted by theory. In this sense, the fusion energy program is partly scientific, partly empirical. Therefore, there is only limited iteration between theory

and experiment. The lack of controlled experimental data needed for the verification of existing theories of trapped particle modes and other microinstabilities has had a negative impact on the understanding of the effects of trapped particles. This lack is partly, but not wholly, responsible for the present unfinished status of trapped particle instability theory. That is, in the absence of experimental guidance, a great variety of microscopic physical effects have been investigated theoretically, some of which may turn out to be physically unimportant in tokamak regimes.

Executive Summary

The evaluation by the participants of the status of the field is as follows:

1. Although there is no experimental verification of the presence of trapped-particle instabilities in tokamaks, work in this field must continue until a conclusive resolution of this question is achieved. In particular, experimental data does not rule out the possibility that drift- and trapped-particle instabilities could significantly contribute to the observed electron thermal transport in present tokamaks such as neutral-beam-heated PLT. Large tokamaks will operate in high temperature, broad profile regimes, which have trapped particles. Lack of theoretical understanding of the effect of these particles on transport should be a cause of concern in evaluating the design of ignition devices.

The theory of trapped particle instabilities must be considered as only one aspect of the general microinstability problem. Tokamak energy transport is known to be anomalous and fluctuations are known to be present. But the effect of trapped particles on the fluctuations, and the relationship of the fluctuations to the transport has not been established. Previous related experiments are no great help because, with the exception of FMI, none of them had toroidal curvature.

2. There has been almost no experimental support to verify theoretical predictions of trapped particle instabilities because the exigencies of the program make it very difficult to plan and build experiments designed to answer questions related to some of the fundamental physical plasma properties even though they may have important physical consequences.

In existing large tokamak confinement experiments programmatic pressures are such as to make it very unlikely that experiments devoted to a single physics issue such as trapped particle instabilities will be performed.

In some cases diagnostic techniques have not yet been developed to the point where they can provide precise information on factors to which transport theories are very sensitive. This includes precise current profiles, temperature gradients, particularly ion temperature profiles, and relative phases of density and

electric field fluctuations. The latter are particularly important, as most simple anomalous transport estimates are based on the choice of phase which yields the maximum transport for a given amplitude.

3. The problem of anomalous transport is complicated by the fact that poloidal field and ohmic heating are tied together by the toroidal current. With high power neutral beam injection this tie will be broken and new insight into transport will be gained.
4. Early prediction of diffusion coefficients due to trapped particle instabilities, such as those based on $\gamma/k_{\perp}^2$ included in WASH-1295, were unduly pessimistic. Present theory forecasts a much less pessimistic scaling of confinement with transport.
5. It is not clear, in view of new developments in theory, what relative contribution to transport is provided by drift and trapped particle instabilities. Other phenomena such as strong turbulence*, resistive tearing modes, stochastic field lines may contribute to transport. How much these contributions will be is not yet certain.
6. At present, most of the theoretical studies of trapped-particle instabilities have been linear. Such theories are useful in identifying the dominant physical mechanisms driving the unstable modes and in predicting relevant threshold conditions for their appearance in tokamaks. However, to actually assess the impact of these instabilities

*Many of the modes discussed can lead to turbulence, so it is not a separate thing, in general. However, "strong turbulence" can be distinct.

on confinement, nonlinear theories must be employed. Little beyond quasilinear theories have been applied to date. In general, present low-frequency microinstability theories are not very useful in predicting the absolute level of transport because processes of nonlinear saturation of unstable modes are not yet well understood.

7. Present linear theories are vastly improved over those that were included in WASH-1295. These now take into account all of the important physical effects such as toroidicity, finite gyroradius, and shear. It is relevant to note this fact because it is precisely the use of oversimplified trapped-particle mode linear growth rates (γ) in the heuristic $\gamma/k_{\perp}^2$ diffusion coefficient formula which led to the erroneous prediction in WASH-1295 that transport would scale as $T^{7/2}$. It is now clear that even if the $\gamma/k_{\perp}^2$ estimate were employed, the use of γ obtained from present linear theories would give completely different results which are much closer to (though still not the same as) the experimentally observed scaling of transport with temperature in tokamaks. Nevertheless, it should be remembered that $\gamma/k_{\perp}^2$ estimates for diffusion coefficients have not been adequately justified on theoretical grounds. In general, it can be stated that theory cannot at present accurately predict the effect of trapped-particle instabilities on transport in tokamaks. The relevant diffusion coefficients cannot be calculated with any certainty until a number of issues are resolved or at least better understood. These involve, for example, the nature of low-frequency

turbulence in a tokamak (whether strong or weak), the effect of stochasticity of magnetic field lines, and the influence of tearing modes. Information on phase relations between the density and potential fluctuations, measurements of ion temperature profiles and low-Z impurity profiles, and the determination of the direction of propagation of unstable waves are among the more important pieces of experimental data required to test the relevance of existing linear and weak turbulence theories.

8. The achievement of reliable predictive capability with respect to the effects of drift and trapped-particle modes on transport will be strongly dependent on the availability of relevant experimental data with which theories can be tested. If data on fluctuation spectra, ion temperature profiles, etc., is made available, there is good reason to be optimistic that in the next few years substantial progress in the development of this predictive capability will be made. However, the scaling laws that are developed may still contain some empirical elements.
9. Nonlinear strong turbulence theory, which may be crucial to interpreting anomalous transport in tokamaks, is in the early stages of development. Analogies with fluid turbulence problems as well as the development of renormalized kinetic theories are currently being pursued. Fluid and particle simulations may provide useful guidance in this very difficult area.

Recommendations

1. In the opinion of the participants, serious thought should be given by ETM to creating an experimental program designed to supply the necessary data base for the predictions of transport and energy confinement, as distinct from scaling experiments. The possibility of giving higher priority on existing large machines to these transport-oriented studies should also be considered.
2. Continuous support should be provided for microinstability theory, including that of trapped particle modes. The emphasis should be placed on the identification of physically important modes and their relation to transport.

DISCUSSION OF SESSIONS OF THE
TRAPPED-PARTICLE INSTABILITIES WORKSHOP

February 12 and 13, 1979

1. How well have trapped-particle theories been able to predict energy losses observed in present and past devices?

Trapped-particle theories have not in any definitive sense been able to predict energy losses. Furthermore, trapped particles and drift modes alone may not be responsible for the observed losses. It is possible that a combination of effects due to weak MHD activity, tearing modes, magnetic braiding, etc. could account for the observed anomalous electron transport.

The reason for this status is as follows:

- (a) It is only recently that computational techniques have been developed to obtain reliable information on the threshold of linear instabilities as well as experimentally verifiable features such as the localization due to ballooning effects and the sensitivity to changes in temperature profile. Recently developed 2-D codes are based on a firm theoretical foundation, but realistic nonlinear theories need to be developed to determine the influence of micro-instabilities on transport.
- (b) Nonlinear theory for toroidal plasmas with shear and finite beta is still in its infancy, although work on it is picking up. As a result, at the present time, no realistic prediction of nonlinear saturation levels is possible at the present time. Weak turbulence

theory of electrostatic modes in simplified geometry is well developed, but may be inadequate.

- (c) Available experimental data is insufficient to determine the nature of low-frequency turbulence, whether weak or strong. There is also no information on the impact (on low-frequency turbulence) of tearing-mode related effects, magnetic field fluctuations, and the presence or absence of convective cells. Without at least some data on the nature of these phenomena, quantitative predictions are risky.
- (d) Detailed experimental data on the things we can measure is insufficient and cannot provide the necessary input into even the linear studies. For example, trapped-particle instabilities depend sensitively on V_T , and such profile information for ions is currently not available. The effect of instabilities depends not only on the amplitude, but also on the phase of fluctuations. Phases have not yet been measured. In general, no adequate experimental information on turbulence in a tokamak is available at present.

2. Are trapped-particle instabilities relevant for current machines and which ones? What about future machines?

High temperature regimes with broad profiles in tokamaks should show a higher fraction of trapped particles. This is something to be concerned about until experimental evidence provides a realistic assessment of the effect of trapped particle instabilities on transport in future devices.

3. What experimental verification is there of trapped-particle instabilities?

Trapped-particle instabilities were observed in DC octopole, linear devices, and FMI. No incontrovertible evidence exists of these instabilities in tokamaks, however. The devices in which more detailed observations were made have no shear and toroidal curvature, except for FMI. In these machines instability growth rates, temperature gradient sensitivity, and instability thresholds were in accordance with theoretical predictions. The experiment in FMI was able to show that as the vertical field was varied, and consequently the trapping region moved from the inside of the torus to the outside, transport varied, while fluctuation levels remained the same. When the electron mean-free-path became equal to the connection length, transport changed from neoclassical to Bohm. It must be emphasized that similar things have not been observed in tokamaks in their present range of collisionality. In actual tokamak devices such as ATC and PLT, microwave and laser scattering diagnostics have indicated that enhanced density fluctuations falling in the drift and trapped-particle mode frequency ranges are present. However, whether these are actually due to drift and trapped-particle modes and whether such modes account for the observed anomalous electron thermal transport are questions which have not been resolved. Nevertheless, qualitative features associated with the fluctuations, such as the observed sensitivity to VT effects and the ballooning-type behavior, are in agreement with theoretical predictions for drift and trapped-particle modes in tokamaks.

4. What could have been done to validate the theory at an earlier point?

The participants felt that the lack of early validation of the theory of trapped-particle instabilities was due to several factors among which the lack of pertinent experimental data is the most important. It should be remembered, however, that it is only relatively recently that tokamaks have clearly progressed into sufficiently collisionless regimes where such phenomena could appear. The workshop members felt that the early shutting down of such devices as FM1 made it difficult to validate the theory against experiment. Experimental data on fluctuation levels and spectra are particularly important because of their complicated nature. For example, studies of fluctuation spectra over a large range of collisionalities showed no clear dependence of transport on fluctuations. The octopole experiment always showed one coherent mode. On the other hand, FM1 showed a broad band of turbulent spectrum at very low shear. Under these low shear conditions, the turbulent density fluctuations showed a power law dependence on frequency but not on wave number. This behavior did not agree with dimensional analysis arguments from strong turbulence theory. The operation in FM1 was shear-dependent. At high shear, the frequency spectrum for a given k was sharp and obeyed the linear dispersion relation. With low shear the spectrum was broad. The transition was sudden and not well understood. No program existed to try and understand the experimental data by designing new experiments.

Tokamaks have high-Z impurities that may mask transitions between

sharp and diffuse fluctuation spectra. It was not until 1977 that atomic physics calculations and bolometer measurements provided the data required to subtract out the contributions of impurities to energy losses. Until that time, fitting transport coefficients to experimental data to explain energy confinement times did not give the codes a predictive capability. The parameter space in which drift and trapped-particle modes must be studied is too large to investigate effectively. Hence, guidance from experimentalists is needed on how to reduce the range of parameters to be studied.

Until about 1976, the individual factors contributing to drift and trapped-particle modes, such as finite gyroradius effects, toroidal effects, etc., had not been combined into a comprehensive picture. This made it difficult to even make realistic predictions regarding the linear properties of tokamak microinstabilities.

5. What relevance do linear theories have to realistic plasmas?

Linear theories give threshold conditions for the onset of instability and initial growth rates. They can provide useful input into weak turbulence nonlinear studies and also give information about experimentally verifiable properties such as spatial localization, sensitivity to ∇T , and the direction of propagation of unstable waves. The mode structure and growth rates become less and less certain as threshold conditions are left behind. There is a possibility of strong turbulence in tokamaks that has no relationship to linear modes, particularly near the plasma edge where density fluctuations of order unity have been observed.

6. Are there any experiments (tokamaks, multipoles, etc.) which can directly identify the saturated spectrum or the transport as due to trapped modes?

FM1 has observed coalescence of modes and appearance of a broad spectrum in low shear cases. The modes were never identified and it is not known what the broad spectrum was due to.

7. What type of small-scale experiments are needed to verify current concepts (versator, microtor, etc.)?

In general, small-scale experiments will have trouble reproducing collisionality regimes of tokamaks close to ignition. To operate in the relevant dimensionless parameter regimes, density must be kept low. At such densities steady discharges present a problem and electrons have a large runaway population. However, drift waves and other modes observed on small devices are closely related to trapped particle modes. The advantage of being able to use probes can provide much information needed by theorists.

Experiments must be done to obtain temperature and density scaling and data on thermal conductivity of a plasma. Devices like beam-heated PLT can yield important information on trapped-particle instabilities because both ions and electrons can be sufficiently collisionless to fall in the banana regime. Machines of the type of ISX-A, TEXT, and Macrotor may be useful for trapped-particle studies, but it is not certain. Small machines cannot do temperature scaling, only density scaling. However, small machines with strong beam heating, such as ISX-B can vary the collisionality and thus study temperature effects.

8. What is the current theoretical and computational status with respect to understanding the saturation processes (convective, nonlinear, etc.)?

The status is primitive. Certain highly idealized weak turbulence regimes have been studied. Weak turbulence in 1-D can be done; for 2-D and 3-D, severe assumptions on the physics must be made. Study of turbulence requires the knowledge of amplitudes and phases of fluctuations. Information on the relative phases of the density and potential fluctuations is currently not available.

A part of the problem affecting nonlinear theory is the lack of an experimental data base and experimental guidance. In the field of fluid dynamics, where no first-principle basis exists, predictive capabilities were developed on the basis of experiments. Plasma physics is better off, in the sense that weak turbulence can be handled by theory on the basis of first principles.

There is very little work being done on strong turbulence. Efforts exist at some national laboratories and some universities, but the people working on this represent a small contingent in this very difficult field.

Particle simulations of drift and trapped-particle modes in a fully toroidal (3D) geometry have been successfully carried out for idealized parameter ranges. However, the simulation of an actual tokamak discharge is still years away because for realistic parameters, the grid-size limitations presently impose prohibitively excessive demands on computer time.

9. How accurate is our understanding of the derivation of transport coefficients, given the fluctuation spectrum?

If the standard assumptions of weak turbulence theory could be justified, then it is possible in principle to develop a consistent theory from which one could determine appropriate transport coefficients. Here again, the phase relationship between the density and potential fluctuations play the dominant role in determining the actual transport. If we allow for magnetic fluctuations, the problem becomes severely complicated with no generally accepted approach currently developed. If we assume that the plasma is completely stochastic, given amplitude and phase information, transport coefficients could be derived. However, there is no experimental basis for such an assumption. Space-time correlation measurements of two points in a plasma could give important information of just how stochastic a plasma is.

10. Can you suggest the type of experimental, theoretical and computational effort, and the time scale for resolution of the trapped-instability transport?

The progress in the field of trapped-particle instabilities will depend to a large extent on the availability of an experimental data base. At the present time, predictions based on linear stability can be made. In the next few years certain hypotheses concerning nonlinear theories will be tested. At the same time, within the framework of linear theories, realistic treatment of electromagnetic waves such as tearing modes will be developed. These studies are in their early stages, but the necessary techniques exist. No such techniques exist for nonlinear theory. People

have been studying nonlinear models of weak and strong turbulence, but the approaches have not been combined into a cohesive whole. The nonlinear activities include investigations of stochastic field lines, ballistic modes or clumps, quasilinear theories, cascading of energy (mode-mode coupling), and electrostatic as well as electromagnetic computer simulation of low-frequency waves. Although particle codes have reproduced trapped-particle-type effects predicted by linear theories in idealized parameter ranges, they have not as yet overcome grid-size and boundary-condition-related problems which prevent the realistic simulation of an actual steady-state tokamak discharge.

11. Status of impurity and alpha-particle transport.

Alpha-particle transport is not as well understood as it should be. Concerning impurity transport, a great deal of work remains to be done. Even neoclassical impurity transport is not fully explored. The work is continuing, but its relevance has yet to be proven as the ions become collisionless. Experimental data seems to indicate that thermalized impurities show the same transport as the rest of the plasma. In PDX there will be measurement of impurity profiles and this could have a large impact on impurity transport calculations. Moreover, the measurement of low-Z impurity profiles should also provide important information which could strongly impact on present linear theories.

The effect of alpha particles on microinstabilities is not well understood. Some of the future efforts in microinstability theories will be in this direction. Experimental input on the relevant velocity and

spatially dependent equilibrium distribution of alpha particles would be most useful in these studies. However, at the present time, there are no good ways of making these measurements.

12. How have trapped-particle theories come to play a major role in tokamak planning?

All the caveats in WASH-1295 have not been able to prevent the community from using very shaky and preliminary diffusion coefficients. However, one must remember that (a) even with WASH-1295 coefficients, TFTR has very good parameters: $T_e = 5$ keV, $\tau_E = 500$ msec, and (b) the predictions of energy confinement for the recent neutral-beam-heated PLT are also consistent with the experimental results. Of course, as mentioned earlier, the scaling with temperature predicted in WASH-1295 is totally wrong.

WASH-1295 provided a useful framework for discussing experiments and planning new devices. Otherwise, purely empirical observations would have been used. However, such empirical scalings were not of much relevance to present machines before Alcator became available.